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Research Article

Operational modeling of a sustainable gas supply chain

Biogas production from codigestion of cattle manure and biomass can have a significant contribution to a sustainable gas supply when this gas is upgraded to specifications prescribed for injection into the national gas grid and injected into this grid. In this study, we analyzed such a gas supply chain in a Dutch situation. A model was developed with which the cost price *per* m_n^3 was presented as a function of scale level (m_n^3/hr). The hypothesis that transport costs increase with increasing scale level was confirmed although this is not the main factor influencing the cost price for the considered production scales. For farm-scale gas supply chains (approximately 150–250 m_n^3/h green gas), a significant improvement is expected from decreasing costs of digesters and upgrading installations, and efficiency improvement of digesters. In this study also practical sustainability criteria for such a supply chain were investigated. For this reason, the digestate from the digester should be used as a fertilizer. For larger scale levels, the number of transport movements and energy use in the supply chain seem to become a limiting factor with respect to sustainability.

Keywords: Biogas / Biomethane / Green gas / Supply chain / Sustainability

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1 Introduction

Biogas production from codigestion of cattle manure and biomass can have a significant contribution to a sustainable gas supply when this gas is upgraded to specifications prescribed for injection into the national gas grid and injected into this grid. In this study, we define "biogas" as being crude gas obtained by fermentation and "green gas" as being gas which is upgraded to natural gas standards, and hence it could be used as a substitute for natural gas. In other literature, this substitute gas is sometimes referred to as "biomethane". Basically with "sustainable", we mean that the needs of the present generation can be met without compromising the ability of future generations to meet their own needs (Brundtland definition). Data on availability of biomass and manure are usually available at a macro level when the potential of a certain region, often a country or even larger, for supplying biomass or generating renewable energy is investigated [1, 2]. However, meeting the ambitions of a future sustainable gas supply, also questions should be answered like: where to build digesters and upgrading installations, where to inject green gas into the gas grid, what is the impact of transport, and what scale level is optimal in this respect. These questions were reviewed before in [3] which showed that green gas injection into the gas grid is a good option for biogas usage from an energy efficiency point of view.

The operational problem sketched above was previously investigated in an Austrian setting [4]. In this study, the costs of biogas and electricity production from maize silage in relation to plant size were investigated. The plant size was also related to the subsidy available and the graduated tariff for green electricity in Austria. No conclusions were drawn on the sustainability of such an energy supply chain. Neither was this the case in a study where four different scenarios for biogas production and application were analyzed economically [5].

It is often assumed that generating renewable energy is sustainable, and therefore often the focus is solely on economy when it comes to design of bioenergy systems. Aiming for large-scale levels seems a logical consequence. The correctness of this may be questioned. At least sound criteria are required to judge sustainability. No general conclusions on the average environmental impact and energy performance of biogas production can be drawn without accurate specification of the biogas system considered. Biogas is not always the best alternative when compared with other bioenergy systems. F.i., if heat is demanded and the raw materials can be combusted, or the arable land can be used for the cultivation of willow, the

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Abbreviations: BM, biomass; **DG**, digester; **DS**, digestate; **HHV**, higher heating value; **IN**, injection; **MN**, manure; **ST**, storage; **TR**, transport; **UP**, upgrading introduction of biogas could increase the emission of greenhouse gases [6]. Another study also concluded that production and use of biogas might present risks for the environment [7]. In a study on bioenergy from grasslands, it was concluded that no general assessment on biodiversity could be made, since the impacts are site specific and depend on the initial situation and the direction of change [8]. F.i., when converting intensive grassland use from forage for dairy farming to biogas feedstock, management intensity might decrease through reducing the mowing frequency. On the other hand, using extensive grassland for biogas feedstock production might conflict with biodiversity targets since attempting intensification would be the obvious target for a farmer.

Also the applicability, economic efficiency, and sustainability of different techniques for energy production from grassland as well as from grassland converted into maize fields, or short rotation poplars under German conditions, were investigated [9]. One of the conclusions in this study was that a verdict about sustainability of an energy supply chain is determined by the significance which is given to different criteria, f.i. focusing on greenhouse gas reduction would lead to another application of land use than focusing on biodiversity.

In this article, we deal with the Dutch situation. Instead of focusing on producing electricity, we focus on upgrading and injection of green gas. Therefore, the goal of this article is to get a better understanding of what a typical (small scale) sustainable gas supply chain, based on biogas production by codigestion, would look like in The Netherlands. More specific, in our study, the focus is primarily on the three northern provinces of The Netherlands (Friesland, Groningen, and Drenthe), because of the above average agricultural activities in this region. The land area of these provinces is approximately 831 600 ha and the average agricultural area from 2005 to 2009 was 267 973 ha (approximately 32.5% of the total land area).

This article further addresses the following subquestions:

(i) What is the cost price of production and grid injection of one m_n^3 green gas based on codigestion in relation to scale level within chosen system boundaries?
(ii) What sustainability criteria should be taken into account for such a supply chain, and what should these criteria be based on?
(iii) How is sustainability related to scale level?

The approach for answering these questions is outlined below.

2 Method and assumptions

A calculation model was developed which enabled us to perform calculations on cost price and sustainability aspects of a green gas supply chain. Such a green gas supply chain based on codigestion may be visualized as shown in Fig. 1. The chain is represented by seven transformation blocks: biomass production (BM), transport (TR) and storage (ST) of biomass and manure, biogas production (DG), digestate handling (DS), biogas upgrading (UP), and green gas injection into the gas grid (IN). The system boundary is resembled by the frame around the blocks. For every block, input and output streams are defined. The main stream is a physical stream, basically from left to right, from seed and cow manure to green gas. The arrows between the blocks represent the routing direction in the chain. Thus, for a given quantity of manure and produced biomass, the produced quantity of biogas and the injected amount of green gas can be calculated. Besides that, for every block, the dotted arrows depict auxiliary streams which are not used further downward in the stream. These auxiliary streams describe costs and sustainability items. With the totals of these auxiliary streams, the cost price and sustainability criteria *per* m_n^3 injected green gas are calculated.

2.1 Assumptions

An average farm in the north of The Netherlands comprises 85 cows and 65 ha land, based on statistics (Dutch Office for Statistics). These numbers determine the amount of cattle manure (MN) and biomass production by this farm and are taken as a reference. If more biomass and manure are needed for a desired biogas production facility, these have to be bought from farmers in the surroundings. Further assumptions in our research, specifically related to the transformation blocks, are discussed below. Because of specific properties and assumptions on manure, this input stream is also discussed. Data and references used in the model and belonging to the assumptions are summarized in Table 1.

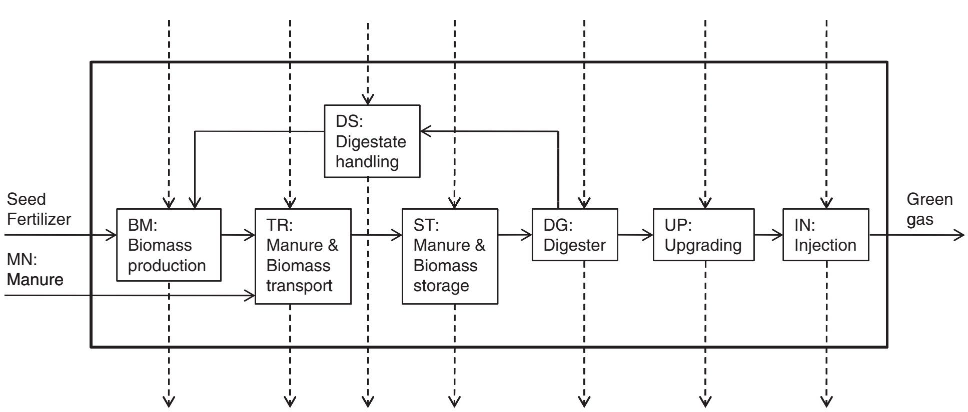

Figure 1. A green gas chain based on codigestion is represented in seven transformation blocks.

2.1.1 Manure (MN)

- Farmers with dairy cattle have a known quantity of manure each year. This has to be stored (shed periods), whether there is a digester or not. Common practice is that the costs for this storage, and environmental effects, are allocated to cattle farming and not to biogas production. For this reason, manure is considered an input into the system.
- In the Netherlands, more manure is produced than can be used as fertilizer. This means that farmers have to pay to get rid of manure although prices vary from region to region. On one hand, this means that when a farmer digests the manure produced on his farm, part of it will be transformed into biogas, and hence the amount of manure left will be less. On the other hand, if a farmer digests the manure of other farmers, the latter will be willing to pay for this. This is resembled in our model by an average, but negative cost price for manure.

2.1.2 Biomass (BM)

- For a desired production of biogas, the amount of needed biomass is taken equal to the amount of manure. According to Dutch legislation, the obtained digestate can be classified as manure and can thus be used as fertilizer.

Table 1. Used data for cost price calculation.

Item	Data	Reference
MN: Manure		
manure production dairy cattle	20 ton/(animal × year)	[10, 11]
manure price	−15 €/ton	[12]
BM: Biomass		
Agricultural land in Friesland, Groningen, and Drenthe	32.5%	
Agricultural land used for energy maize	25%	
Nitrogen use limit maize	150 kg/ha	Dutch legislation
Phosphate use limit maize	75 kg/ha	Dutch legislation
Savings on fertilizer	3 €/ton digestate	Commercial price
Crop yield silage maize	45 ton/ha	[4, 13, 14] (statline.cbs.nl)
Maize price	28 €/ton	[15–17]
TR: Transport		
Capacity tractor (biomass)	30 m^3 (14 ton)	[18, 19]
Capacity truck (manure and biomass)	30 ton (100 m^3)	[18, 19]
TR costs tractor	0.85 €/km	[20]
TR costs truck	1.24 €/km	[20]
Energy consumption tractor transport	2.1 MJ/(ton km)	[18]
Energy consumption truck transport	1.3 MJ/(ton km)	[18]
DG: Digester		
Biogas yield cow manure	25 m_n^3/ton	[11, 21, 22]
Biogas yield silage maize	175 m_n^3/ton	[4, 22]
Methane content biogas	55.6 vol%	[21]
Investment cost function	$0.0082{*}Q^{0.9042}{*}10^6$	Based on [15][a)]
DS: Digestate handling		
Max. nitrogen from digestate on land	170 kg/ha	Dutch legislation
Max. phosphate from digestate on land	75 kg/ha	Dutch legislation
UP: Upgrading		
Upgrading method	Water wash	
CH_4 efficiency	97%	[23]
CH_4 content green gas	89.4 vol%	
Investment cost function upgrading	$81\,532{*}Q^{0.4551}$	Based on [15][a)]
IN: Injection		
Distance installation to grid	500 m	
Piping costs	130 €/m	[24]
General		
Depreciation	12 years	SDE (Dutch subsidy regime)
Interest rate	7%/a	SDE (Dutch subsidy regime)
Operating hours installations	8000 h/a	[12, 24]
Electricity price	14 €ct/kWh (from grid)	Commercial price

[a)] Q, biogas production (m_n^3/h).

- The needed land area is assumed to be circular with the digester in the center point. This stresses that the activities are as local as possible. It is evident that making another assumption would influence cost price and sustainability negatively.
- Maize silage production is used as the reference case. F.i., [25] confirms that maize is often used for codigestion because of its high biogas yield.
- Maize production covers 25% of the farmer's land. Although the number is more or less arbitrarily chosen, we assume that fallow lying land can be used for growing energy crops and part of the current crops can be replaced by energy crops. Dutch statistics show less than 1% of the arable land being fallow lying. Decreasing the 25% criterion would mean less energy production in a given area and higher transport costs for the same amount of biomass (increasing distances). It is obvious that further study is required concerning land use.

2.1.3 Transport (TR)

- Tractors are assumed to be used for transport of biomass on the farmers' land. For transport of manure and biomass from other areas, trucks are used.

2.1.4 Storage (ST)

- Investment costs are 800 times biogas production in m_n^3/h, based on [15].

2.1.5 Digester (DG)

- A one-stage, Continuously Stirred Tank Reactor, mesophylic digester is assumed.
- The methane content of the biogas is calculated based on methane production potentials of the manure and maize.

2.1.6 Digestate (DS)

- The digestate is assumed to have a commercial value as fertilizer. Besides that, digestate must be used as a fertilizer because of sustainability reasons. This is discussed in Section 2.3.
- The amount of digestate which is allowed on the land is determined by maximum values for nitrogen and phosphate. If extra fertilizer is needed by the crops, this needs to be supplied by artificial fertilizer.

2.1.7 Upgrading (UP)

- In our research, it is assumed that the upgrading installation is at the same location as the biogas plant, and hence no extra transport of biogas is needed.
- The chosen upgrading technique is water wash. This is not only a commonly used technology, but it also gives the opportunity to remove the CO_2 to a specified level. In our case, we desire the green gas to have a similar Wobbe-index as Dutch natural gas, *i.e.* a CH_4 content of 89.4%. Further, it is assumed that 3% of the CH_4 in the biogas is lost during the upgrading process, *i.e.* the methane efficiency is 97%.

2.1.8 Injection (IN)

- Concerning injection, we assume a more or less arbitrary 500 m pipeline connection between the upgrading installation and a distribution grid injection point. The green gas is compressed to 8 bar. Furthermore, it is assumed that the grid can handle the green gas flow without limitations.

2.2 Costs

In an economic analysis of biogas production in Ireland, a sensitivity analysis was needed to identify the economic parameters which are most critical to economic feasibility [26]. The price of biomethane and the cost of feedstock turned out to be the most critical, whereas overall capital and operating costs were less significant.

In our study, the costs will also be divided into capital and operating costs. The data for this calculation are collected from the literature and personal communication. The depreciation and interest rate correspond to the Dutch subsidy regime. Investment costs for plants as a function of scale level were analyzed by putting data from the literature in a spreadsheet and interpolating the data points by a function of the type $y = a \cdot x^b + c$ with an R^2 value of at least 0.9. The total cost price of one m_n^3 green gas is divided into costs for the transformation blocks as shown in Fig. 1. In this way, it is possible to check the hypothesis that the total costs will decrease with increasing scale level, but transport costs will increase.

The chosen scale of green gas production is between a small production plant 100 m_n^3 ($\sim$170 m_n^3 biogas) and 1200 m_n^3 ($\sim$2000 m_n^3 biogas). The latter represents a large-scale plant which is currently under development in The Netherlands.

2.3 Sustainability

Researchers seem to use different criteria to assess the sustainability of processes. It was shown that the energy input into (large scale) biogas systems corresponds to 20–40% of the energy content in the biogas produced, but no conclusions were drawn what this means in terms of sustainability [27]. Emissions (CO_2, CO, NO_x, SO_2, HC, CH_4, and particles) of biogas systems were analyzed from a life-cycle perspective for different biogas systems based on different raw materials [28, 29]. A general conclusion was that biogas systems normally lead to environmental improvements. This is often due to the indirect environmental benefits of changed land use and handling of organic waste products (*e.g.* reduced nitrogen leaching, emissions of ammonia and methane), which often exceed the direct environment benefits of replacing fossil fuels

Table 2. Identified criteria for sustainability.

Theme	Indicator	Quantification (prescribed)	Quantification (added by authors)
Greenhouse gas balance	Nett emission reduction when compared with fossil energy, including application (*i.e.* measured for the total supply chain)	At least 50% (**a**)	–
Competition with food, local energy supply, medicine, and construction materials	Availability of biomass for food, local energy supply, construction materials, or medicine should not decrease	Not available	25% of farm land used for energy production (**b**). Energy needed for production and grid injection of one m_n^3 green gas should not exceed the energy content (higher heating value) of one m_n^3 green gas (**c**)
Bio diversity	No deterioration of protected areas or valuable ecosystems	Plantations should not be in or near protected areas. Reference year for wood feedstock is 1994 (FSC 10.9), for palm oil 2005 (RSPO 7.3), for others 2006 (**d**)	–
	Knowledge about active protection of the local system	Management plan for active protection of local ecosystem (**e**)	–
Profit	No negative effects on local and regional economy	Not available	–
	Knowledge about active contribution to improving of local economy	Report required about active contribution to improving of local economy. Transparent communication with local population is demanded (**f**)	–
Prosperity (no negative effects on the well-being of employees and local population)	Working circumstances of employees	Complying Social Accountability 8000 and Tripartite Declaration of Principles concerning Multinational Enterprises and Social Policy as indicated by the International Labour Organization (**g**)	–
	Human rights	Complying Universal Declaration of Human Rights (concerning: nondiscrimination, freedom of association, child labor, forced and compulsory labor, disciplinary practices, security practices, and indigenous rights) (**h**)	–
	Property and user rights	No land use without agreement of sufficiently informed original users (**i**). Land use is described in detail and officially approved (**j**)	
		Official property and use of population is respected (FSC 3) (**k**)	–
	Social circumstances of local population (active contribution to improvement)	Not available	Odor (**l**) No. of transport movements (**m**)
	Integrity	Companies in the supply chain comply the Business Principles for Countering Bribery (n)	–
Environment	Waste management.	Comply local and national laws	
		Apply Good Agricultural Practice guidelines on integrated crop management	The mass of cosubstrate should not exceed the mass of manure (**o**)[a)]
	Use of agricultural chemicals (including artificial fertilizer)	Local, international and EU law	Cycles of carbon and nutrients (**p**)[b)]

Table 2. Continued

Theme	Indicator	Quantification (prescribed)	Quantification (added by authors)
	Preventing erosion and exhaustion of soil	Not available	–
	Active improvement of quality and quantity of surface and underground water	Not available	–
	Emissions into air	EU laws	NO_x, SO_x, N_2O, and NH_3 specific (**q**)

a)Dutch legislation on fertilization.
b)As much as possible. This is also determined by Dutch legislation.

by biogas (*e.g.* reduced emissions of CO_2 and air pollutants). Gerin *et al.* [30] confined their study to the energy and CO_2 balance as the core of calculating specific green certificates, but recognized that a more general assessment of sustainability should include other issues, f.i. other greenhouse gases, energy needed for seed, machine and plant production, *etc.* Vetter and Arnold [31] investigated besides the CO_2 balance of a green gas chain, the humus balance, erosion effects, and biodiversity of biomass production for this chain. Another study discussed the assessment of sustainability as well, but was confined to land-use systems [32]. Yet another study chose a different way for assessing the sustainability of energy production from grassland [9]. In the integrative sustainability concept they followed, no prior distinction is made between economic, environmental, and social dimensions. From this concept, seven substantial preconditions for sustainable development were derived:

(i) Sharing the use of natural resources fairly.
(ii) Sustainable use of nonrenewable resources.
(iii) Sustainable use of the environment as a sink.
(iv) Protection of human health.
(v) Sustainable use of renewable sources.
(vi) Conservation of the cultural function of nature.
(vii) Securing an autonomous existence (f.i. employment and securing wages).

Based on these objectives, 16 indicators were chosen which were quantified as much as possible.

In The Netherlands, six themes were proposed to assess sustainability for biomass production, which show many similarities with the objectives mentioned above [33]. The first three are specific for biomass; the last three resemble the more general triple P (people, planet, and profit). In this approach, it is not known beforehand where in the world this biomass is produced, which make that the criteria have a general character although it is assumed that the biomass is used in The Netherlands. This enables us to relate them to a scale factor in a later stage (because of the focus of our research). We chose to take these six themes as a basis. This choice is due to the Dutch setting of our research, and is in good correspondence with the aforementioned literature. Moreover, the Dutch green gas certificate trade is based on these criteria (under development). The themes with indicators and quantification are summarized in Table 2. The quantified indicators are marked in bold letter. Some additions were made concerning the quantitative indicators where appropriate.

The interdependency between sustainability and scale level is evident. When biogas production is still relatively small scale in The Netherlands, criteria concerning economy and prosperity in developing countries are not really relevant. This might change significantly when production is scaled up and biomass is imported from abroad. Also, with small-scale biomass usage, waste flows or energy crops on fallow lying land could be used. On small scale, this will have no impact on matters like biodiversity. But up-scaling biomass production might cause problems in this respect if that means that relatively more land will be used for one type of biomass.

Concerning criterion (**a**), it is not integrated in our model, but calculations point out that a biogas supply chain based on digestion meets this requirement [12]. And also that the emission of greenhouse gases can be reduced by some 75% when biogas replaces fuel oil in district heating plants or petrol in light-duty vehicles despite the fact that the emission from vehicles, *etc.*, used in biogas production is included [6].

In our approach, the criteria (**b**), (**o**)–(**q**) are incorporated in the calculation model, *i.e.* results of the model always meet these criteria. The preference of using digestate as a fertilizer (criterion (**p**)) from a sustainability point of view was also shown by [31].

Just like (**b**), criterion (**c**) is somewhat arbitrary. One might argue that it does not matter how much energy is needed for producing green gas when the used energy is sustainable as well. But even in this case land is needed for producing energy. This land could be used for producing food as well. Energy needed for fodder which is transformed into manure is not incorporated in the model, because the manure is considered a stream which is available anyway. Embodied energy in biomass storage facilities is considered to be negligible.

Criteria (**d**)–(**g**) and –(**n**) are relevant, but can be neglected at the scale level considered in this study, because these criteria concern mainly social circumstances in developing countries or comprise management activities by biogas producers.

Criterion (**k**), odor, can be considered a problem in general, but is very subjective. The closer to populated areas, the more this is considered a problem. We assume this negligible, as the digester is on a farm.

Criterion (**m**), number of transport movements, has shown to be a barrier in practice, considering the resistance by people living in the neighborhood of new biogas installations. One truck movement is defined as a truck driving to and from the installation. The number of allowable transport movements is difficult to assess with respect to sustainability. At the moment, we consider this as a political decision. As a rough estimation, it could be stated that truck movements are possible during 250 (working) days a year. With eight working hours on each day and one allowed transport movement *per* hour this would be 2000 allowed transport movements *per* year.

3 Results

3.1 Costs

The results, including the total cost price of one m_n^3 of green gas, are shown in Fig. 2. In this figure, it is shown that the total cost price of one m_n^3 green gas at a production rate of 100 m_n^3/h is significantly higher than when producing 1200 m_n^3/h. Costs *per* m_n^3 of biomass and manure remain constant with increasing scale level. Costs of transport and digestate slightly increase, whereas costs for storage, digesting, upgrading, and injection decrease. A subdivision of relative costs at 150, 300 (which is a little above the average for The Netherlands), and 1200 m_n^3/h is shown in Fig. 3.

3.2 Sustainability

As stated before, several criteria are automatically fulfilled by incorporating them into the model. The number of transport movements is mentioned as a criterion for sustainability. The relationship between scale level and transport movements is shown in Fig. 4. With the aforementioned fictitious limit on transport movements of 2000 *per* annum, the transition point from sustainable to nonsustainable is at some 250 m_n^3/h. For the energy consideration, this transition point is at approximately 150 m_n^3/h, (Fig. 5), when the given limit (**c**) in Table 2 is taken into account. A subdivision of energy need at 150, 300, and 1200 m_n^3/h is summarized in Table 3. In this table, it is summarized that at a green gas production of approximately 300 m_n^3/h and more, the energy need is almost fully determined by transport of manure, biomass, and digestate (at 300 m_n^3/h it adds up to 94%).

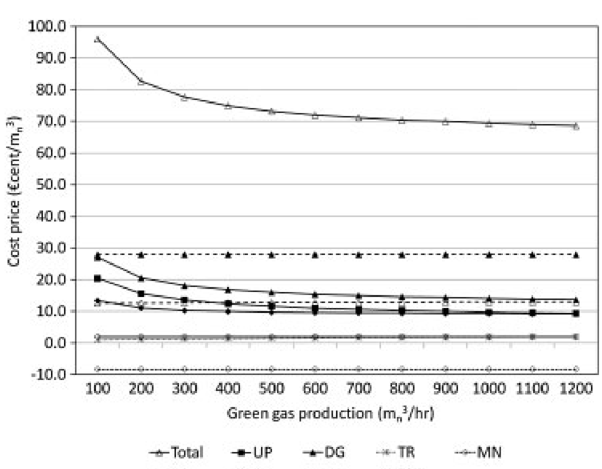

Figure 2. Cost price of green gas (MN, manure; BM, biomass; TR, transport; ST, storage; DG, digester; DS, digestate; UP, upgrading; IN, injection).

4 Discussion

To check the calculations, a comparison was made with a reference calculation [12]. In this reference, a cost price for green gas was calculated on the basis of a water wash upgrading system. The required heat necessary for this technology is supplied by burning biogas in a boiler. The surplus heat from gas washing is sufficient for heating the digester. A mass reduction of 10% by digestion is assumed. In Table 4, data of a relatively small system are given (270 m_n^3/h biogas or 150 m_n^3/h green gas).With these data, the calculated cost price for green gas injection is 81.3 €ct/m_n^3 for 2010 (without the Dutch energy investment subsidy). The corresponding cost price in our model is 87.2 €ct/m_n^3. The main reason for this difference is that the reference model assumes a cosubstrate price of 23 €/ton, where we assume 35 €/ton.

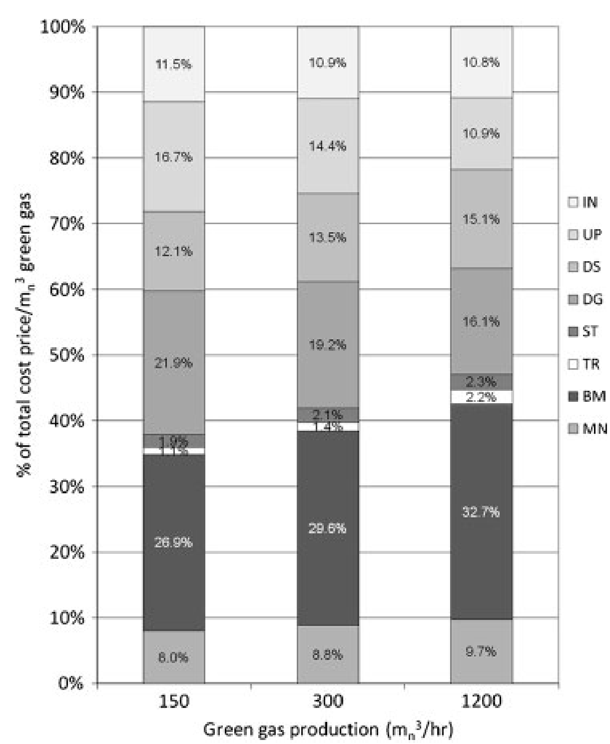

Figure 3. Subdivision of relative costs at a green gas production rate of 150, 300, and 1200 m_n^3/h. The total costs for these production rates are 87.2 €ct/m_n^3 (at 150 m_n^3/h), 77.6 €ct/m_n^3 (at 300 m_n^3/h) and 68.6 €ct/m_n^3 (at 1200 m_n^3/h). Although the cost price for manure is negative, the value is shown as a positive value for presentation reasons.

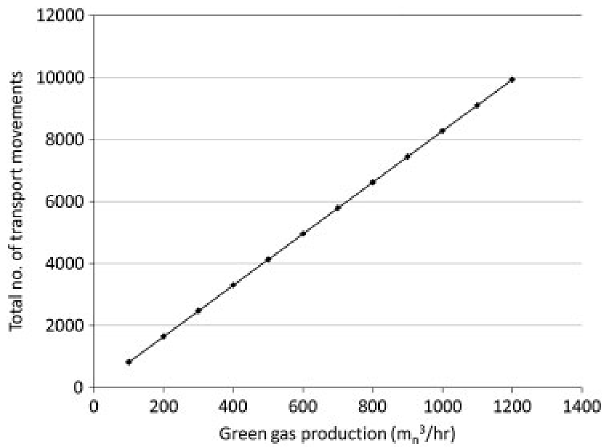

Figure 4. Total number of transport movements. The needed transport for the removal of digestate is included.

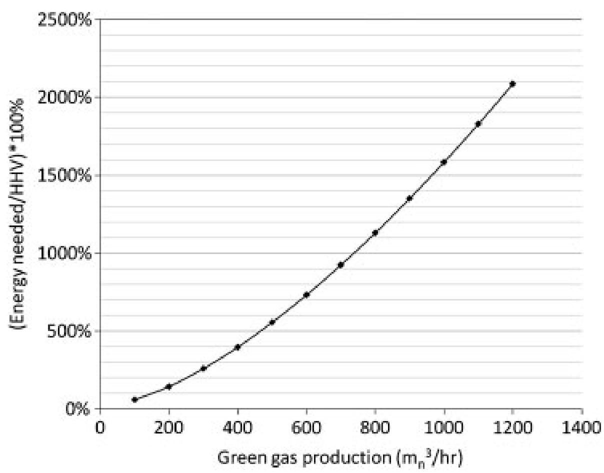

Figure 5. The ratio of the needed energy for the production and injection of one m_n^3 green gas and the higher heating value (HHV) of green gas. In the model, the HHV of green gas is 39.8 MJ/m_n^3.

Table 3. Subdivision of energy need for producing green gas (injected into the gas grid) for three production capacities (150, 300, and 1200 m_n^3).

Green gas production (m_n^3/h)	BM (%)	TR (%)	DG (%)	DS (%)	UP (%)	IN (%)	Total (%)
150	3.3	42.7	5.8	39.7	3.9	4.6	100
300	1.2	50.9	1.4	43.3	1.4	1.8	100
1200	0.1	55.5	0.1	43.9	0.2	0.2	100

Figures 2 and 3 show that the more decentralized the biogas plants are, *i.e.* relatively small gas production rates, the more relevant the costs for digesting and upgrading are. On the other hand, relative costs for biomass and transport increase with increasing scale level. For small-scale levels, the cost price of green gas is high, but sustainability criteria hinder up-scaling. A positive influence of lower biomass prices is evident [26], but this is determined by the market. Possibilities for minimizing the green gas cost price might be found in increasing biogas production in digesters or lowering the investment costs for digesters. A sensitivity analysis of these is shown in Fig. 6. It seems that optimizing biogas production is more promising than decreasing the plant costs. Possibilities for moving the sustainability limits to larger scale levels are minimizing the energy use of trucks and again biogas production (Fig. 7). Both options seem to be promising although minimizing the energy use of vehicles is an autonomous development.

Table 4. Data of the reference system for production of green gas based on codigestion of manure and biomass [12].

Item	Data
Biomass and manure	
Trade value manure	−15 €/ton
Cosubstrate type	50% energy maize and 50% biomass with lower costs (waste products, sometimes less energy content)
Cost price cosubstrate	23 €/ton
Transport and storage	
Costs transport manure	5 €/ton
Digester	
Operating hours	8000 h/a
Investment	4490 €/m_n^3/h biogas
Fixed O and M costs	295 €/m_n^3/h biogas
Energetic efficiency digester	67%
Methane content biogas	56%
Upgrading	
upgrading technique	Water wash
Investment	3880 €/m_n^3/h biogas
Fixed O and M costs	385 €/m_n^3/hr biogas
Methane efficiency gas cleaning	99.9%
General	
Electricity price	14 €ct/kWh (from grid)
Reference scale	270 m_n^3/h green gas
Depreciation	12 years

It was stated before that a green gas production based on codigestion in The Netherlands has an envisioned potential of 1500 million m_n^3 *per* year [16]. In our model, the green gas production would be 1350 m_n^3/ha agricultural area. With the aforementioned agricultural area of 267 973 ha, the potential would be 362 million m_n^3 in the three northern provinces of The Netherlands. These three provinces cover approximately 25% of the Dutch land area, but consist of relatively much agricultural land. Hence, even with the optimistic assumption of 25% agricultural land use for green gas production, this target would be very hard to achieve.

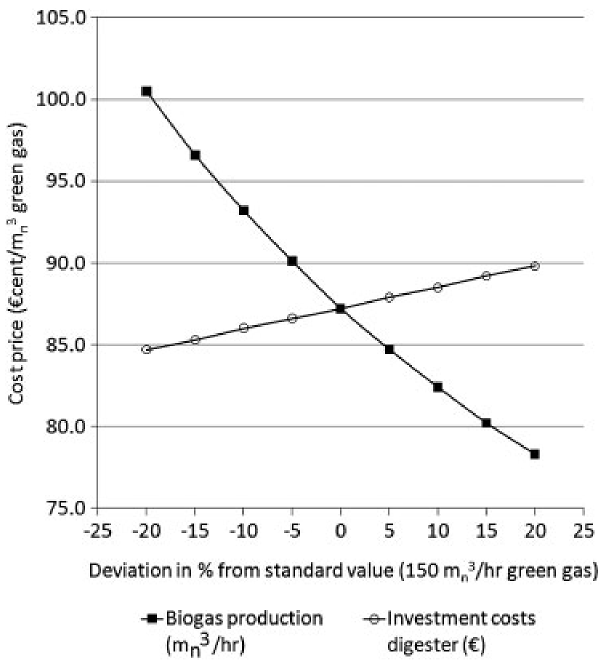

Figure 6. Influence of deviations in digester efficiency (biogas production) and investment costs of a digester on the cost price of green gas (the cost price at the standard value is 87.2 €ct/m_n^3).

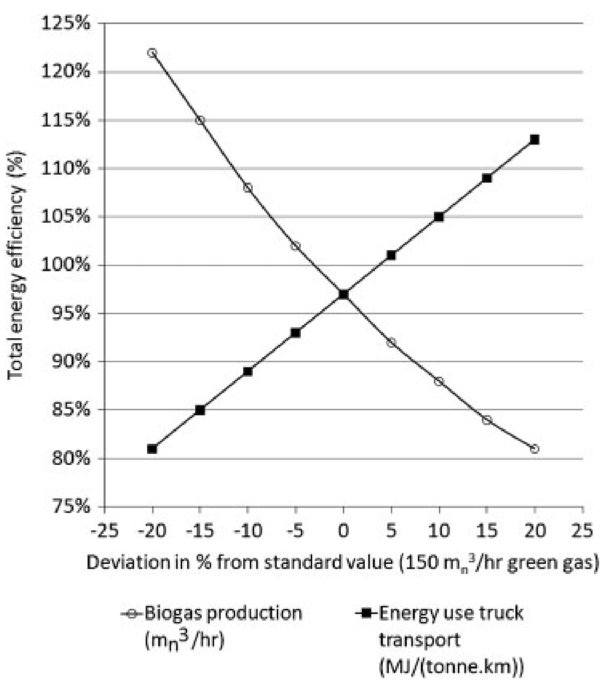

Figure 7. Influence of deviations in digester efficiency (biogas production) and the energy consumption of trucks on the total energy efficiency of a green gas chain (*i.e.* the energy needed for producing 1 m_n^3 green gas/HHV of green gas; the energy efficiency at the standard value is 97%).

5 Conclusions – future research

In this research, a reference green gas supply chain was analyzed. Energy maize was taken as a cosubstrate for digestion. It was found that transport costs increase with increasing volume of green gas, and that digester, upgrading, and injection costs decrease with increasing scale level. A more detailed analysis may be useful in order to find out which other biomass types are useful as a cosubstrate and if an optimal substrate mix can be calculated in a given situation. If the maximum of 2000 transport movements were to be taken as a strict limit, the focus should be on decentralized, relatively small-scale energy production systems. This would mean that digesters and upgrading installations should become cheaper and the efficiency should increase. Especially from developments in upgrading techniques, a lot is expected. Research into increasing biogas output of digesters is promising in this respect as well. The presented research is based on a model which describes the throughput of a gas supply chain which is a quasi-static way of describing the supply chain. The next step is to optimize the model in the sense of matching supply and demand, *i.e.* dynamic simulation of a green gas supply chain. The objective of such an optimization should be to find ways to further decrease costs.

Transport movements can be considered a sustainability item with regard to quality of life. However, it is difficult to find a strict limit for the allowed number of transport movements. Above, an estimation of truck movements is given. Determining the allowable number of movements might be more a matter of policy than science. On sustainability in general, more comments could be made as well. In this article, we referenced to several studies on this subject. It seems that scientists as well as policy makers are still searching for sound sustainability criteria. Sound criteria on environmental indicators such as "preventing erosion and exhaustion of soil" and "active improvement of quality and quantity of surface and underground water" are still lacking. The Cradle-to-Cradle approach might give some interesting new insights in this respect [34]. We believe that the kind of research we present here is still under development. This might influence the results and the most optimal scale level of sustainable energy installations as well.

In this research, we assumed the necessity of fully upgrading biogas to natural gas standards. Further research might show that this is not always necessary. The possibilities of mixing off-spec gas with natural gas in terms of economics should be investigated. Preconditions for mixing would depend on composition of the gas, the ratio of gases to be mixed and the requirements on the mixture. Finally, expanding the model to describe a regional situation with more than one digester is interesting with regard to finding optimal logistics.

Conflict of interest

The authors have declared no conflict of interest.

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